Are national barrier inventories fit for stream connectivity restoration needs? A test of two catchments

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Conflict of interest

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Abstract

Catchment-scale river reconnection programmes require barrier inventories for restoration planning, yet barrier inventories are variable in extent and quality internationally. To test the degree to which barrier databases, in this case for England, are fit for purpose, we made a comparison of the national database (mostly originating from desk-study) for two catchments, the Wear and the Tees, against detailed walkover surveys. We surveyed 701 km (32.8%) of stream length, stratified by stream order, altitude and subcatchment and recorded natural and artificial barriers. Only 22.7% of barriers identified in the walkover survey were present in the national database, including low-head (<5 m) artificial structures (32.3% representation), artificial barriers ≥5 m (14.3% representation) and culverts (0% representation). 18.9% of artificial barriers in the national database were found, during field survey, to have been breached naturally. Mean densities of artificial barriers were 0.68 barriers km^{-1} and 0.45 barriers km^{-1} in the Wear and Tees respectively, significantly higher than in the national database. Stream connectivity restoration in England may be hampered by the incomplete national barrier inventory; we recommend careful checks of barrier inventories as they are developed internationally.

Keywords: River barrier, dam, fish passage, habitat restoration, culvert, connectivity

1. Introduction

Artificial obstacles such as dams, weirs and sluices along rivers have been constructed to control floods, and provide water for human consumption, irrigation and power supply (Jackson and Marmulla, 2001; Birnie-Gauvin *et al.*, 2017aGalib *et al.*, 2018). Culverts and fords have been built to provide transport crossings or to route water through urban environments (Warren and Pardew, 1998; Price *et al*., 2010). In-stream barriers, whether artificial or natural (e.g. waterfalls, glacial sediment plugs) can interrupt longitudinal and lateral connectivity, and so alter hydrology, sediment transport, nutrient flow and the movement of biota (Mueller *et al*., 2011; Grill *et al.*, 2015). Natural barriers such as waterfalls can affect the biogeography, genetic structuring and diversity of organisms by limiting their dispersal, and partially or completely isolating populations, facilitating local adaptation (Whiteley *et al*., 2010; Torrente-Vilara *et al*., 2011). It is the density, distribution and nature of artificial obstacles that causes concern for damaging impacts to natural river processes and the ecosystems that are inherently linked to these (Lehner *et al*., 2011; Jones *et al*., 2019).

Removal or mitigation of anthropogenic barrier effects along rivers is a major aspect of river restoration programmes (Kemp and O'Hanley, 2010), including in Europe where large amounts of river infrastructure were installed during the agricultural and industrial revolutions, some of which is now redundant (Birnie-Gauvin *et al*., 2017a). Hydromorphology, comprising a stream section's hydrological regime, continuity and morphological condition, is an element of quality assessment under the Water Framework Directive (WFD) in European Union member states. In multiple EU states many rivers are failing, or at risk of failing, to reach good ecological condition due to impaired hydromorphological quality (Atkinson *et al*., 2018; Jones *et al*., 2019). River obstacles can alter habitats, disrupt dispersal between habitat patches, restrict or prevent migration and eventually lead to a decline in the abundance of sensitive species and biological diversity (Louca *et al*., 2014;

Favaro *et al*., 2014; Birnie-Gauvin *et al*., 2017b). Populations of diadromous fishes such as European eel (*Anguilla anguilla*) and Atlantic salmon (*Salmo salar*) have reduced significantly at least in part due to the impacts of artificial barriers (Parrish *et al*., 1998; Piper *et al*., 2013).

Globally, most large dams are recorded in databases (Lehner *et al*., 2011; Grill *et al*., 2015), and their impacts on river systems are well studied (Van Looy *et al*., 2014). There are fewer such databases for small-scale barriers (but see Sheer and Steel 2006; Januchowski-Hartley *et al*., 2013; Atkinson *et al*., 2018; Jones *et al*., 2019) and they are mostly incomplete. Jones *et al*. (2019) found that the current barrier databases for Great Britain underestimated man-made barrier numbers by 68%, mostly due to under-recording of small barriers. Although small-scale barriers such as weirs, ramps and fords may have lesser impacts on biota per location than large dams, low-head barriers are much more abundant (Januchowski-Hartley *et al*., 2013), and their cumulative effects on biota may be significant (Lucas *et al.,* 2009; Kemp and O'Hanley, 2010).

Globally there are 16.7 million reservoir impoundments, and 99.5% are small structures (reservoir surface area < 0.1 km^2) (Lehner *et al*., 2011). According to a geographic information system (GIS) based desk study of maps (Entec, 2010), there are nearly 25 000 weirs and similar structures in rivers of England and Wales, of which 3000 of the barriers need connectivity restoration to meet EU WFD targets (Environment Agency, 2013). However, in order to mitigate the negative impacts of in-stream barriers, an effective strategy for river reconnection is needed as part of the restoration process (Kemp and O'Hanley, 2010; Tummers *et al*., 2016). To do this barriers need to be mapped, measured, categorised and a barrier inventory generated (Januchowski-Hartley *et al.*, 2013; Atkinson *et al*., 2018). The inventory can be used to prioritise which obstacles to remove or mitigate, depending on modelled benefits, restoration costs and objectives (King *et al*., 2017). For river management, an inadequate restoration plan may lead to inefficiencies or waste of effort (Kemp and O'Hanley, 2010), and the accuracy of barrier inventories can directly affect connectivity restoration planning. So it is necessary to understand the true numbers, distribution and types of in-stream barriers of whole catchments for effective river connectivity restoration.

Across Europe there is much variability in the extent to which river barriers have been mapped and recorded (Garcia de Leaniz *et al*., 2018). England is regarded as having one of the more complete and up-to-date barrier databases, originating from a desk-based study to map hydropower opportunities (Entec, 2010; Jones *et al*., 2019). Ground-truth comparison of the Great Britain barrier database surveyed under 0.2% of stream length at 1:250 000 resolution, stratified across Great Britain (Jones *et al*., 2019), with the possibility that more intensive validation surveys at the individual catchment level might generate different outcomes. To test the degree to which current national river barrier databases, in this case for England, may be fit for river-connectivity restoration purposes, we carried out intensive, stratified walkover surveys of two medium-sized catchments and compared them with the national river barrier database. Since one aim of our study was to measure stream connectivity for biota, especially fish, we recorded the occurrence and characteristics of in-river obstacles of natural and anthropogenic origin, as well as the existence and typology of fish passage devices and barrier removals.

2. Methods

2.1 Study area

The Rivers Wear and Tees were chosen for study because they are medium-sized catchments, somewhat typical of the variable topography and land uses occurring across large parts of Great Britain (Figure 1). The Wear and Tees are 110-km long and 160-km long respectively, both rising in the Pennine Hills and flowing eastwards to the North Sea. The lower reaches of both rivers pass through agricultural, industrial and urban areas, and the upper parts of the catchments were heavily exploited for metal mining in the 17th-19th centuries. Coal mining and processing occurred widely through the lower and middle Wear catchment in the 18th-20th centuries. Water storage reservoirs occur in the upper catchments of both rivers, especially the Tees, where they were built, in part, for maintaining industrial water supply to downstream reaches. Large parts of the catchments are agricultural but they also have an extensive road and rail network, including river crossings, a proportion of which are disused transport routes originating during the industrial revolution. There is also a legacy of agricultural and industrial mills and weirs, almost all of which no longer serve their original purpose, but many are now linked to or near residential dwellings. This river infrastructure is similar in diversity and origins to much of that which developed in Britain and across Europe in the agricultural and industrial revolutions (Downward and Skinner, 2005). Both rivers have recovering Atlantic salmon populations, following dramatic reductions in industrial and urban pollutant loadings in recent decades, although the Tees' recovery has been slow, probably due to a tidal barrage opened in 1995. Further details of the catchments' characteristics are provided in Supplementary Information S1.1.

2.2 National river barrier database

In England, the national river barrier inventory used for management and longitudinal connectivity restoration planning was produced, and is held and managed, by the Environment Agency (EA) of England (Jones *et al.*, 2019). The EA barrier database was originally created from a desk-based study to map hydropower opportunities at river channel barriers across England and Wales (Entec, 2010), generally at sites having an in-channel drop greater than 1 m. The dataset of barrier locations was derived from an Ordnance Survey (OS) Master Map (Entec, 2010). Any structure on the map, passing across the river channel and listed as a dam, weir or waterfall was identified and mapped in the database. Therefore the database includes natural and anthropogenic barriers. Barrier height information was extracted from LiDAR (Light Detection and Ranging) and SAR (Synthetic Aperture Radar) datasets. Subsequently the EA has added sites to this database as they have been identified, particularly tidal water management sluices, and additional artificial barriers identified by local EA teams. The EA barrier inventory dataset used in this study was the same as that in Jones *et al.* (2019), generated in January 2018.

2.3 Independent barrier validation – stratified walkover surveys

In order to provide a quality assessment of the national barrier inventory, walkover surveys, stratified by stream order, altitude and position within the catchment (Jones *et al.*, 2019) were carried out in order to record natural and anthropogenic barriers. Only permanently-flowing streams were surveyed. Since the context of our study was from a longitudinal connectivity restoration viewpoint, particularly as regards fish passage, we recorded obstacles that had the potential to limit upstream movement of fish at normal to low flows (~Q_{50}-Q_{90}), while acknowledging that maintaining free downstream-migration passage is also important (Silva *et al.*, 2018). Obstacles to free movement of fishes depend on obstacle characteristics (especially height and gradient), fish species and environmental conditions (Kemp and O'Hanley, 2010; Barry *et al*., 2018). In our surveys, any artificial structure having a vertical or steeply-sloping (> 45 degrees) step, exceeding 0.2 m in height, was regarded as a potential obstacle to weakly-swimming taxa (Utzinger *et al*., 1998; Tummers *et al*., 2016). More gently sloping structures (e.g. culverts) without an obvious step were regarded as potential obstacles if they had a fall in height along their length exceeding 0.5 m and/or were very constrained (e.g. pipe culverts), and/or very shallow (< 3 cm at ~Q_{90}, e.g. many artificially-lined culverts; Tummers *et al*., 2016). This is a simpler framework than the SNIFFER and ICE rapid barrier assessment methods (Barry *et al*., 2019) but deliberately so as even small obstacles may impact dispersal and recolonization of non-jumping fish species (Tummers *et al*., 2016). We also regarded any natural waterfall or cascade exceeding 0.5 m high as a potential obstacle, as well as extensive bedrock sills with water depth < 3 cm. River restoration projects rarely seek to alter natural connectivity barriers, such as waterfalls, and so barrier inventories tend only to record obstacles of anthropogenic origin. This study recorded natural obstacles in order to provide a context to the distribution of anthropogenic barriers, and to enable comparison to the national inventory of such barriers. Further, understanding the distribution of both natural and anthropogenic barriers in a catchment can play a role in better catchment planning for restoration of migratory species populations (Silva *et al*., 2018) and/or for limiting the spread of invasive species by managed habitat fragmentation (Rahel and McLaughlin, 2018).

Walkover surveys of almost all but the smallest catchments rely upon subsampling (Jones *et al.*, 2019), or progressive development of a database over a period of many years (Sheer and Steel, 2006). In our study the OS Open Rivers (1: 25 000) GIS was used for river mapping and subsampling the Wear and Tees for walkover surveys. On this system and scale, first-order streams (Strahler, 1957) normally had a field-observed wetted channel width of less than 3 m (J. Sun, pers. obs.). Typically, stream reaches in the lower resolution (1: 250 000) European Catchments and Rivers Network System (ECRINS: European Environment Agency, 2012) database are recorded as a Strahler stream order lower than in this study, reflecting the lower spatial resolution of the ECRINS database. Thus, most first order streams recorded in our study do not exist in ECRINS, and first order streams listed for the Wear and Tees in Jones *et al.* (2019) which employed ECRINS, were typically recorded as second order streams in our, finer resolution, study.

In order to stratify walkover surveys across a range of stream orders, altitudes and sections within the Wear and Tees catchments, each of these watersheds wassplit into upper, middle and lower subcatchments (Figure 1) based upon EA operational catchment areas. Three or four tributaries were quasi-randomly selected from each operational catchment for conducting the walkover survey. Each of these provided multiple sections of Strahler first- to fourth-order streams to survey. Besides these tributaries, the main channels of the Rivers Wear, Tees, and sections of the Browney (Wear), Skerne (Tees) and Leven (Tees) were included in the walkover survey, in order to sample extensive lengths of stream orders 4 and 5. This is because longitudinal connectivity obstacles on main river channels are particularly important to identify, especially for diadromous migratory fish (Silva *et al*., 2018), even if they tend to be well recorded in existing barrier inventories (Jones *et al*., 2019). Although the Browney (containing River Deerness), Skerne and Leven were defined as operational catchments by the EA, we categorized the Browney in the Lower Wear, the Skerne in the Middle

Tees Catchment and the Leven in the Lower Tees subcatchments based on their geographic locations (Figure 1). Additionally any online, large artificial water bodies (> 10 ha) evident on 1:25 000 maps, and with an obvious dam, were visited and obstacle characteristics recorded by visual inspection, reference to maps and any information available on their construction.

Field surveys were carried out by the authors. For each tributary selected, the survey normally covered the whole stream length (and for all adjoining streams) from the main river confluence upstream towards the source, to the limit of the channel evident on OS Open Rivers 1: 25 000. The location (British national grid reference) and altitude (m above sea level) of physical obstacles, both natural and artificial, were recorded as they were encountered. The barrier type, height, gradient, pool depth (immediately below obstacle) and length (for culverts and concrete channels) were measured and a brief description made. Photographs for each barrier, with a scale bar alongside, were taken.

At any artificial obstacles where modification had occurred with the apparent aim of improving river connectivity for fishes (fishways and other passage easements) we gathered information on that from field measurements, as well as from EA and Rivers Trust records. We also recorded sites where barriers had existed in the recent past (national database) but had collapsed, breached or been removed deliberately within the areas surveyed.

2.4 Data analysis

Barrier data from the field were entered into a spreadsheet inventory. Each barrier was given a unique code and associated with a barrier photograph. The Strahler stream orders of all channel segments in the two catchments were identified using OS Open Rivers (1:25 000). The cumulative distances field surveyed and the proportion of field-surveyed river length in each stream order were calculated by QGIS (version 2.18.4) using river segment lengths from OS Open Rivers.

Barriers from the EA database identified as occurring in non-qualifying habitat (not on OS 1: 25 000 Open Rivers network or found to be dry, so not representing permanent aquatic habitat) were excluded from analysis. Artificial barrier density was calculated for each river section for a given stream order, using the total number of artificial barriers divided by total river length (km) in that section.

We compared artificial and natural barrier densities in the national database with field surveyed barrier densities for the same river sections. Artificial barrier heights measured in the field survey were compared across the two catchments and also with the distribution of barrier heights from the national database. Where data were not normally distributed they were transformed log (x+1) before statistical comparison. ANOVA was used to compare barrier densities between stream orders, and between upper, middle and lower catchment areas. *t*-tests were used to compare mean barrier height between the catchments. Paired *t*-tests were used to compare barrier heights and densities between the walkover survey data and national database. All tests were run in SPSS (Version 22).

The overall barrier abundance of the whole catchment was estimated by two methods. In Method one (simple uprating), barrier density was calculated for each stream section having a particular Strahler stream order, then mean barrier density across all surveyed stream sections (Wear n = 83, total length 280 km; Tees n = 62, total length 421 km) was multiplied by the total stream length in the catchment. In Method two (uprating by stream order proportions) the same calculation was applied to estimate total numbers of barriers for total length of each Strahler stream order in a catchment and these subtotals for Strahler stream orders were summed to generate a value for the entire catchment.

3. Results

3.1 River Wear catchment

In the Wear, 752 km (to nearest km) of stream channel length were mapped from OS Open Rivers 1: 25 000 (1st order, 330 km; 2nd order 202 km, 3rd order, 75 km, 4th order 44 km, 5th order 100 km) and a total of 280 km (37.3%) of the Wear catchment stream length was field surveyed. Across field-surveyed reaches of the Wear, 364 barriers were recorded, 41.2% (n = 150) of which were artificial barriers and 58.8% (n = 214) were natural barriers (waterfalls and cascades) (Figure 2). Mean artificial barrier height was 1.40 m (95% CI Bootstrap: 0.64 - 2.38 m), and mean natural barrier height was 1.31 m (95% CI Bootstrap: 1.02 - 1.58 m). Most barriers were located in first and second order streams, comprising 78% (n = 117) of artificial barriers and 79% (n = 169) of natural barriers. Artificial barriers were most frequent at low altitudes, while the opposite occurred for natural barriers (Figure 2). Among artificial barriers within our field survey area, 19.2% (n = 29) had a fishway or other passage mitigation, seven further barriers had been deliberately removed for connectivity restoration and another 11 washed away (Figure 3).

The mean artificial barrier density of the Wear catchment was 0.68 barriers/km (95% CI Bootstrap: 0.47 - 0.91 barriers/km). Barrier density did not differ across stream orders 1-3 (ANOVA, $F_{2,74}$= 2.600, p = 0.081), for which sufficient samples sizes were available. Lower barrier densities occurred at stream orders 4 and 5 (Table 1, not statistically tested due to small sample size). The density of artificial barriers did not differ between the upper, middle and lower Wear subcatchments (ANOVA, $F_{2,80}$ = 1.657, p = 0.197). The total number of artificial barriers in the Wear, estimated by simple uprating, using an average artificial barrier density of 0.68 across the entire field surveyed area was 512 (Table 2). The total number of artificial barriers estimated by Method 2, summing the estimated numbers for all Strahler stream orders was 479 (Table 2).

The EA's national barrier database contained 254 barriers for the Wear, 69 (artificial and natural) of which were within our field-surveyed areas (Figure 4). The national database included one of four barriers larger than 10 m (Figure 5), none of which incorporated fishways. Since 15 of the artificial barriers in the national database for the Wear had been washed away or removed already, only 54 barriers (33 artificial and 21 natural barriers) were valid in the national database for the field-surveyed area (Figure 5). The artificial barrier density calculated from the national database (0.04 barriers/km) was significantly lower compared with the walkover-surveyed barrier density (paired t-test on transformed data, t_{82} = 6.630, p < 0.001). Overall, 78.0% (n = 117) of artificial barriers and 90.2% (n = 193) of natural barriers were missed in the national database for walkover-surveyed areas of the Wear (Figure 3). Artificial barriers in the national database for the Wear were exclusively weirs, but approximately equal numbers of weirs, culverts and bridge aprons occurred in the walkover survey (Figure 4). None of the small cascades and waterfalls (< 2 m high, n = 192) identified in field walkovers were recorded in the national database. A significant difference occurred between walkover survey barrier (natural and artificial combined) heights (mean ± SD, 1.33 ± 3.79 m) and national database barrier heights (4.10 ± 3.89 m) (independent *t*-test on transformed data, t_{422} = 9.237, p < 0.001), showing the national dataset concentrates on larger obstacles.

3.2 River Tees catchment

In the Tees, 1389 km of stream channel length were recorded in 1: 25 000 OS Open Maps (1st order, 667 km; 2nd order 321 km, 3rd order, 183 km, 4th order 97 km, 5th order 120 km) were recorded. A total of 421 km river length were walkover-surveyed, covering 30.3%of stream length in the whole Tees catchment. Across the field-surveyed area, 322 barriers were recorded, of which 65.1% (n = 211) were natural and 34.9% (n = 111) were artificial barriers (Figure 2). Artificial barriers were most frequent at low altitudes, while the opposite occurred for natural barriers (Figure 2). Mean artificial barrier height was 2.95 m (95% CI Bootstrap: 1.73 - 4.45 m), and mean natural barrier height was 2.28 m (95% CI Bootstrap: 1.78 – 2.96 m). Heights of natural (Independent *t*-test on transformed data, t_{435} = 4.109, p < 0.001) and artificial barriers (Independent *t*-test on transformed data, t_{260} = 2.848, p < 0.001) were significantly higher in the Tees than Wear catchment. Most (82.9%) of natural barriers in the Tees were located in first and second order streams. In field-surveyed reaches of the Tees, 67.6% (n = 75) of artificial obstacles were weirs and dams. Overall, 16.2% (n = 18) of artificial barriers surveyed had a fishway or other passage mitigation (Figure 3). Two further barriers had been deliberately removed for connectivity restoration and another 10 had collapsed (Figure 3).

The mean artificial barrier density of the Tees catchment was 0.45 barriers/km (95% CI Bootstrap: 0.29 - 0.62 barriers/km). Barrier density did not differ across stream orders 1-3 (ANOVA, $F_{2,53}$ = 0.745, p = 0.479). High order streams tended to have lower densities of barriers (Table 3). There was no difference in the density of artificial barriers between the upper, middle and lower Tees subcatchments (ANOVA, $F_{2,59}$ = 8.38, p = 0.410). Using the global average artificial barrier density of 0.45 barriers km^{-1} uprated by total stream length, the total number of artificial barriers in the Tees was estimated as 625 (Table 2), while summation of the subtotals per Strahler stream order gave an estimated total of 576 (Table 2).

In the national database, a total of 113 barriers were recorded within our field survey area of the Tees. The national database did not record eight dams higher than 10 m (none of which have fishways) that exist within the Tees catchment. As 11 of the artificial barriers in the national database had been removed for river restoration purposes or washed away (Figure 3), 102 barriers (49 artificial and 53 natural barriers) were valid in the national database (Figure 5). The artificial barrier density in the Tees catchment from the national database (0.09 barriers km^{-1}) was significantly lower than for the same stream segments in the walkover survey (paired *t*-test on transformed data, t_{61} = 5.317, p < 0.001). 55.9% (62) of artificial barriers and 74.9% (158) of natural barriers were missed in the EA database compared with the walkover survey (Figure 5). None of the culverts (n = 14) or aprons (n= 9) identified in the field survey were recorded in the national database. Mean barrier height (4.80 ± 4.49 m) from the national database was significantly higher compared to the walkover survey database (2.49 ± 6.05 m) within the same surveyed areas (independent *t*-test on transformed data, t_{429} = 7.482, p = 0.01).

4. Discussion

Our study provides a test of the adequacy of the English national barrier database for two typical medium-sized catchments, albeit neighbouring catchments within the same geographic region. We find large-scale under recording of obstacles, including most large water storage dams. The study has generated the first intensive but, as yet still incomplete, inventory of artificial and natural barriers in the Wear and Tees catchments and provides a valuable resource for river restoration work in the future. Our study indicates that 77.3% of the in-stream barriers in both catchments were absent in the national database, including 68.6% of artificial barriers and 82.6% of natural barriers. The field-validated barrier densities are significantly higher by comparison with the EA national database barrier densities. The EA barrier inventory is likely to be one of the more complete inventories in Europe (http://www.amber.international). So it also seems likely that in other countries where barrier inventories have been mapped by desk study there may be similar levels of error.

A total of 13 artificial barriers taller than 10 m (nine in the Tees, four in the Wear) occurred in our barrier database, but only two of these were in the EA national barrier inventory, even though almost all are water supply reservoirs, none of which have fish passage facilities. Three of these dams were present in the Global Reservoir and Dam (GRanD) database (Grill *et al.*, 2015) and hence in the database generated by Jones *et al*. (2019), which also contains one additional non-duplicated barrier from the EA national database. In the UK, the Inventory of Reservoirs Database contains 273 individual reservoirs, which account for 90% of UK reservoir storage (Durant and Counsell, 2018) but evidently, within the Wear and Tees catchments, most of these are not integrated into the EA's national barrier database. The UK's Inventory of Reservoirs Database was missing four dams with a height greater than 10 m compared to our database for the Wear and Tees. Thus, not only does the EA national obstacle inventory contain a small fraction of all artificial barriers, it also excludes some of the largest and most significant river barriers. Most of these large dams in the Tees and Wear are located in headwater valleys, where the majority of natural barriers also occur. None of the large Tees/Wear dams have fishways. Athough several fishways were incorporated into their dam designs when built over a century ago, they are now defunct (M. Lucas, pers. obs.). It could be argued that fishways would be of little use at these headwater dams due to elimination, by the dams, of fluvial nursery habitat necessary for migratory salmonids (Silva *et al*., 2018). These dams have also led to starvation of gravel transport to the river reaches immediately downstream, impacting habitat quality for salmonid spawning and other native rhithral biota (B. Lamb, pers. comm.). On the Tees, the largest of these impoundments, Cow Green Reservoir, is also upstream of several large natural barriers that are impassable in an upstream direction by fish. Nevertheless, national barrier inventories must include all large obstacles, and most smaller ones, in order to be fit for purpose for river-basin planning activities.

Fishways and other passage easements are the most common engineering mitigation for loss of river connectivity (Silva *et al*., 2018). However, in order to restore river processes in fragmented rivers, removal of redundant barriers is increasingly used and recommended (Bednarek, 2001; Poff and Hart, 2002; Tummers et al., 2016) because hydromorphic as well as ecological processes are reinstituted (Roni *et al*., 2008; Birnie-Gauvin *et al*., 2017b). In our field survey area only 21.5% (56/261, Wear and Tees combined) of artificial barriers had been mitigated with fishways/easements or removed. Only nine of the 261 structures (3.5%) in our survey areas across the two catchments had been deliberately removed. However, 21 weirs recorded on the EA's desk-study generated national database and within this study's walkover area were recorded as washed out by floods, or perhaps by other informal mechanisms (e.g. non-reported dismantling by humans). This represents 8.1% (21/261) of all artificial structures recorded. Many of these structures were old mill weirs, some centuries old and often of blockstone design, the remains of which were evident. The high energy of upland rivers such as the Wear and Tees during spate can breach such structures when not kept in good repair. Evidently a significant proportion of the artificial barriers listed in the English national barrier database are unlikely to be barriers any more, particularly within upland high-energy river systems.

Atkinson *et al.* (2018) showed that river barrier inventories generated from mapping methods, as is mainly the case for the English river barrier inventory, must be validated by visiting all potential barriers identified by desk study. Maintaining accurate and up-to-date river barrier inventories must be a priority for river reconnection restoration, for example to optimize the efficacy of barrier mitigation/removal actions at the catchment scale (King *et al.*, 2017; Barry *et al*., 2019). Most ongoing stream reconnection actions in English catchments, including the Tees and Wear, are currently planned by regard to the potential for converting 'failing' WFD stream segments to 'good ecological condition' without fully considering the basin-wide distribution and characteristics of artificial and natural barriers. Because many river barriers in England are privately, rather than state-owned, and ownership is, in many cases, unknown or contested, barrier mitigations or removals frequently occur at sites where there is greatest facilitation by stakeholders and owners, not necessarily at the highest priority sites in restoration terms.

In Great Britain, a recent study indicated that 68% of artificial barriers recorded in the field are missing from the existing database and a large proportion of the missing barriers are structures less than 1-m high (Jones *et al*., 2019). That study adopted the coarser 1: 250 000 scale ECRINS GIS (European Environment Agency, 2012) for determining field surveys and missed most of the smaller stream channels we recorded as Strahler first order at 1: 25 000 mesh. At 1: 250 000 Jones et al. (2019) validated 0.2% of river network, whereas at 1: 25 000 we validated 37% and 30% by stream length of the Wear and Tees catchments respectively. The percentages of artificial barriers estimated to have been missed in the national barrier inventory for the Wear and Tees were 78% and 55.9% respectively. Despite the difference in spatial resolution and intensity of survey between these studies, under-reporting of artificial barriers for the Wear and Tees are not greatly different to the overall 68% under-reporting value estimated by Jones *et al.* (2019) for the whole of Great Britain and gives confidence in the validity of that estimate. The importance of spatial resolution for barrier inventories is highlighted by the fact that in our study over 70% of river network length for the Wear and Tees comprised first and second order streams, while for Ireland the value is 77% (McGarrigle, 2014). In an audit of the accessibility of juvenile Atlantic salmon habitat in the River Nore, Ireland,, Gargan *et al.* (2011) excluded first order streams and those with a gradient exceeding 4%, on the basis that those streams are used little by salmon. By contrast, first and second order coastal streams are widely used by sea trout *Salmo trutta* for spawning and nursery areas in Denmark (Aarestrup *et al.*, 2003). Clearly, the spatial resolution for barrier audits needs to take careful consideration of the environmental restoration objectives.

Although desk-study generation of barrier inventories using historic maps, overhead imagery and transport infrastructure routes is a useful tool (Januschowski-Hartley *et al*., 2013; Atkinson *et al*., 2018), there is a growing consensus that these must be validated by field-surveying (Atkinson *et al*., 2018; Jones *et al*., 2019). The easiest way of removing false-positives is to visit potential obstacles identified but this does not avoid missing artificial barriers not apparent from maps and overhead imagery, especially in urban or heavily tree-lined areas (Atkinson *et al*., 2018). Despite catchment-scale walkover survey methods being time consuming, the method provides high-quality data to generate a reliable barrier inventory for catchment-scale connectivity restoration. We recommend that walkover surveys are undertaken, subcatchment by subcatchment, to develop comprehensive barrier inventories, which are regularly updated as barriers are added, removed or mitigated in order out to enable effective river-connectivity restoration planning and actions. Even when catchment barrier inventories are complete, periodic walkover audits, possibly supplemented by drones or other technology where topography allows, will need to be undertaken in order to take account of natural breaches and intentional removal of redundant obstacles.

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Conflict of interest

The authors declare no conflict of interest.

Data Availability Statement

Raw data are available from the lead author by request.

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Table 1. Summary of fieldwork surveyed river length (km) under each stream order in the Wear catchment, and the mean artificial barrier density at each stream order.

Catchment	Stream order	River length (km)	River section (*n*)	Artificial barrier number (*n*)	Artificial Barrier density per section (n/km)	
					Mean	SD
Wear upper	1	14.5	22	4	0.24	0.64
	2	12.3	7	14	1.54	0.98
	3	8.5	2	2	0.15	NA
	4	10.5	1	5	0.47	NA
	5	17.9	1	3	0.17	NA
Wear middle	1	10.2	13	14	1.04	1.54
	2	20.9	7	19	0.37	0.66
	3	9.4	2	1	0.10	NA
	4	8.1	1	2	0.25	NA
	5	16.9	1	4	0.24	NA
Wear lower	1	28.7	15	24	0.80	1.04
	2	42.9	7	40	1.19	0.74
	3	7.8	2	10	1.18	NA
	4	6.2	1	1	0.16	NA
	5	65.3	1	7	0.11	NA
Wear overall	1	53.5	50	42	0.62	1.11
	2	76.1	21	73	1.03	0.94
	3	25.7	6	13	0.48	0.72
	4	24.9	3	8	0.29	0.13
	5	100	3	14	0.17	0.05
Combined		280.2	83	150	0.68	1.03

Table 2. Estimated numbers of artificial barrier numbers in the Wear and Tees using Method 1 (average density across all stream segments in field survey zone multiplied by total catchment stream length) and Method 2 (sum of estimated barrier numbers for combined length of each Strahler stream order).

Catchment	Method	Stream order	Length	Density	95% CI		Estimated number	95% CI	
Wear	1	total	752.323	0.68	0.47	0.91	512	354	685
	2	1	330.602	0.62	0.33	0.96	205	109	317
		2	202.32	1.02	0.63	1.44	206	127	291
		3	74.898	0.44	0.08	1.02	36	6	84
		4	44.418	0.29	0.16	0.47	13	10	18
		5	100.085	0.13	0.1	0.16	17	15	19
		combined					479	267	729
Tees	1	total	1388.727	0.45	0.29	0.62	625	403	861
	2	1	667.429	0.58	0.3	0.89	387	200	594
		2	321.13	0.23	0.1	0.43	74	32	138
		3	182.513	0.46	0.15	0.87	84	27	159
		4	97.136	0.28	0.05	0.51	27	5	50
		5	120.519	0.03	0	0.05	4	0	6
		combined					576	264	947

Table 3. Summary of fieldwork surveyed river length (km) under each stream order in the Tees catchment, and the mean artificial barrier density at each stream order.

Catchment	Stream order	River length (km)	River section (*n*)	Artificial barrier number (*n*)	Artificial Barrier density per section (n/km)	
					Mean	SD
Tees upper	1	15.0	17	3	0.50	1.10
	2	23.6	7	4	0.27	0.52
	3	23.4	2	8	0.32	NA
	4	20.5	1	1	0.05	NA
	5	14.0	1	0	0	NA
Tees middle	1	41.6	9	32	0.86	0.78
	2	22.7	5	5	0.19	0.11
	3	49.0	2	11	0.37	NA
	4	0.0	0	NA	NA	NA
	5	37.5	1	2	0.05	NA
Tees lower	1	22.7	9	10	0.47	0.69
	2	32.7	4	9	0.23	0.36
	3	6.2	2	1	0.69	NA
	4	42.9	1	22	0.51	NA
	5	69.0	1	3	0.04	NA
Tees overall	1	79.3	35	45	0.58	0.94
	2	79.0	16	18	0.23	0.36
	3	78.6	6	20	0.46	0.44
	4	63.4	2	23	0.28	NA
	5	120.5	3	5	0.03	0.02
Combined		420.8	62	111	0.45	0.77

Captions of figures

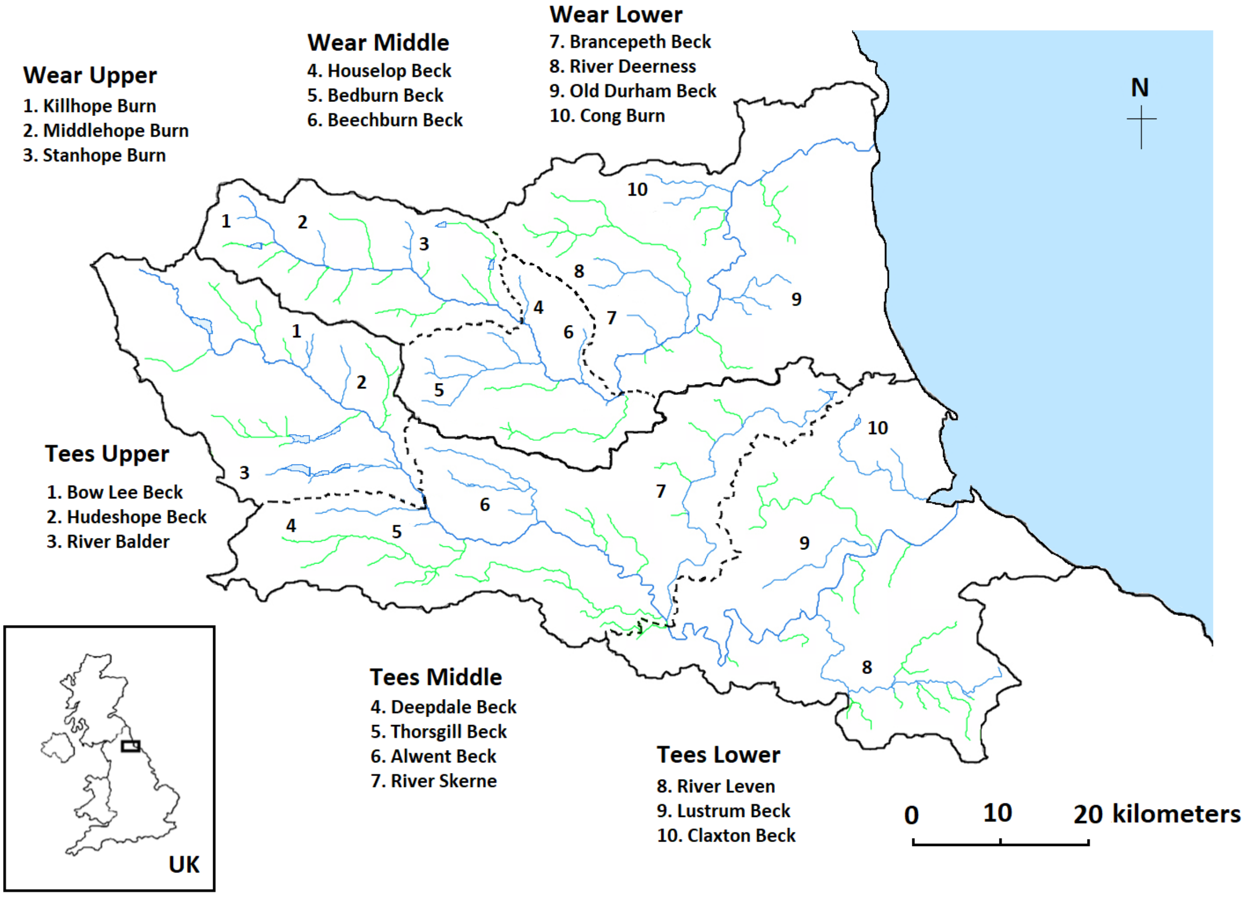

Figure 1. The location of the Wear and Tees catchments including their sub-catchments in England, as well as the location of field surveyed rivers (blue). The main River Wear and River Tees in each sub-catchment has also been surveyed.

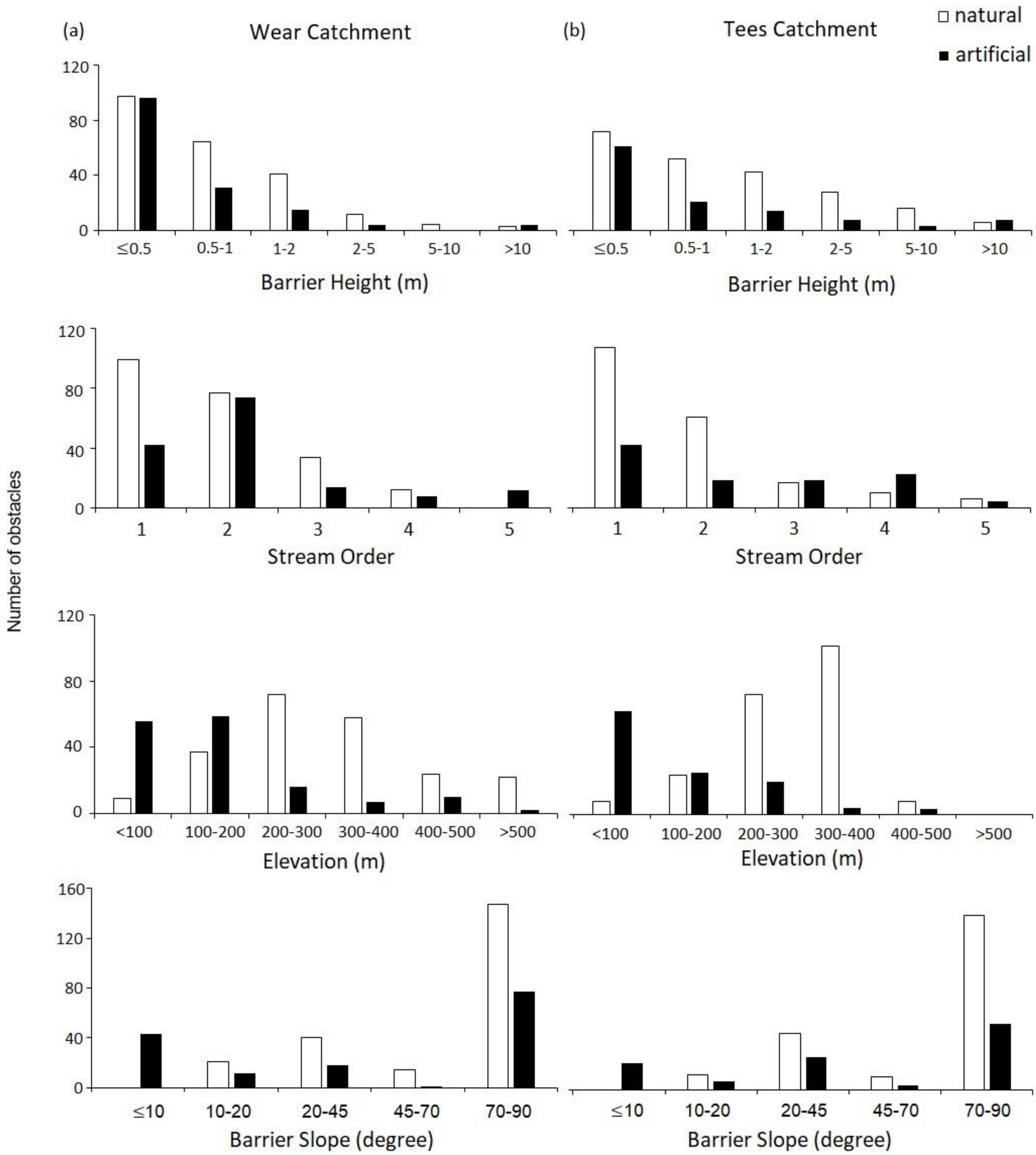

Figure 2. Natural and artificial barrier height, stream order, barrier elevation and slope on (a) the Wear and (b) the Tees catchment.

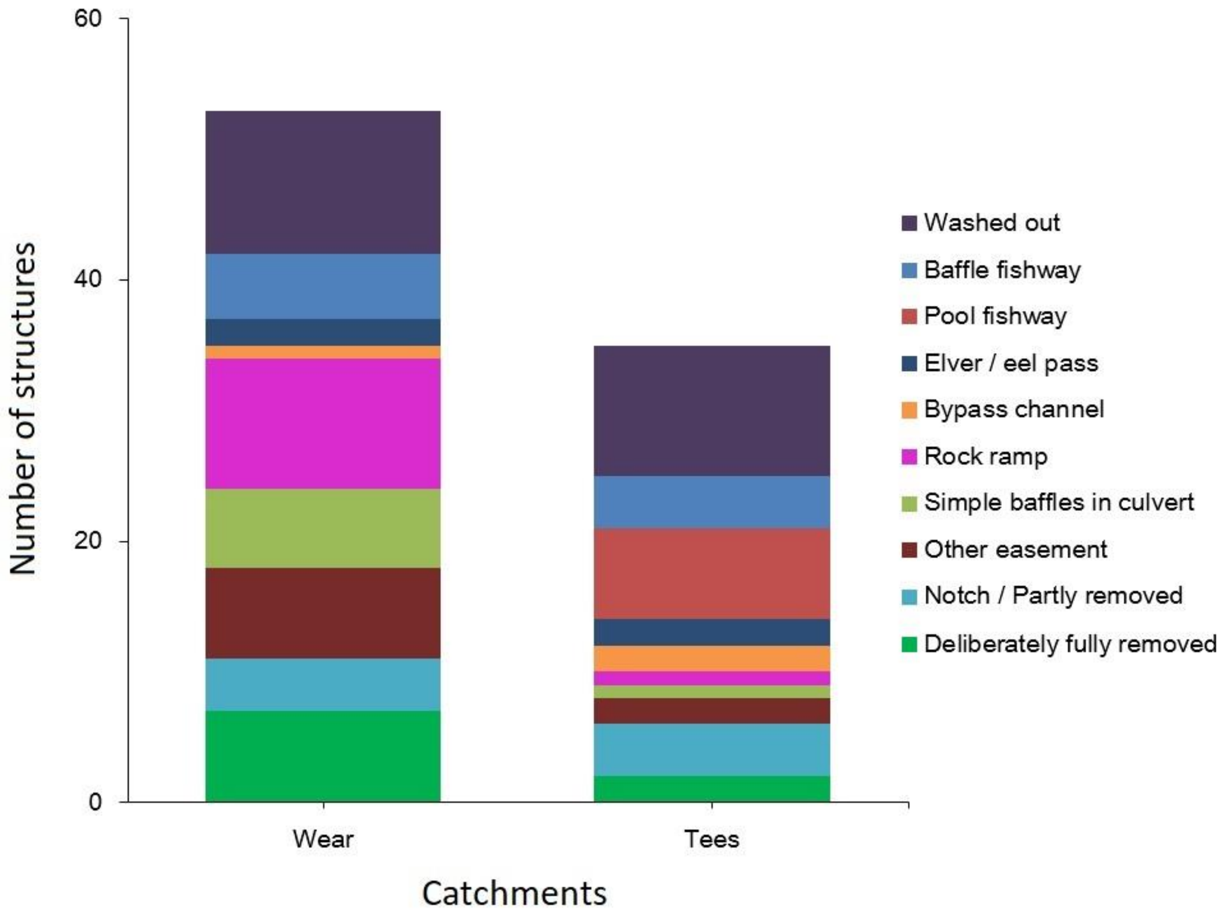

Figure 3. Numbers of artificial barriers deliberately removed for connectivity restoration, washed out, or fitted with fish passage mitigations in the Wear and Tees. Elver / eel pass refers to bristle and /or studded substrate. 'Other easements' refers mainly to pre-impoundments built downstream of the main obstacle to raise the water levels and facilitate passage by jumping species.

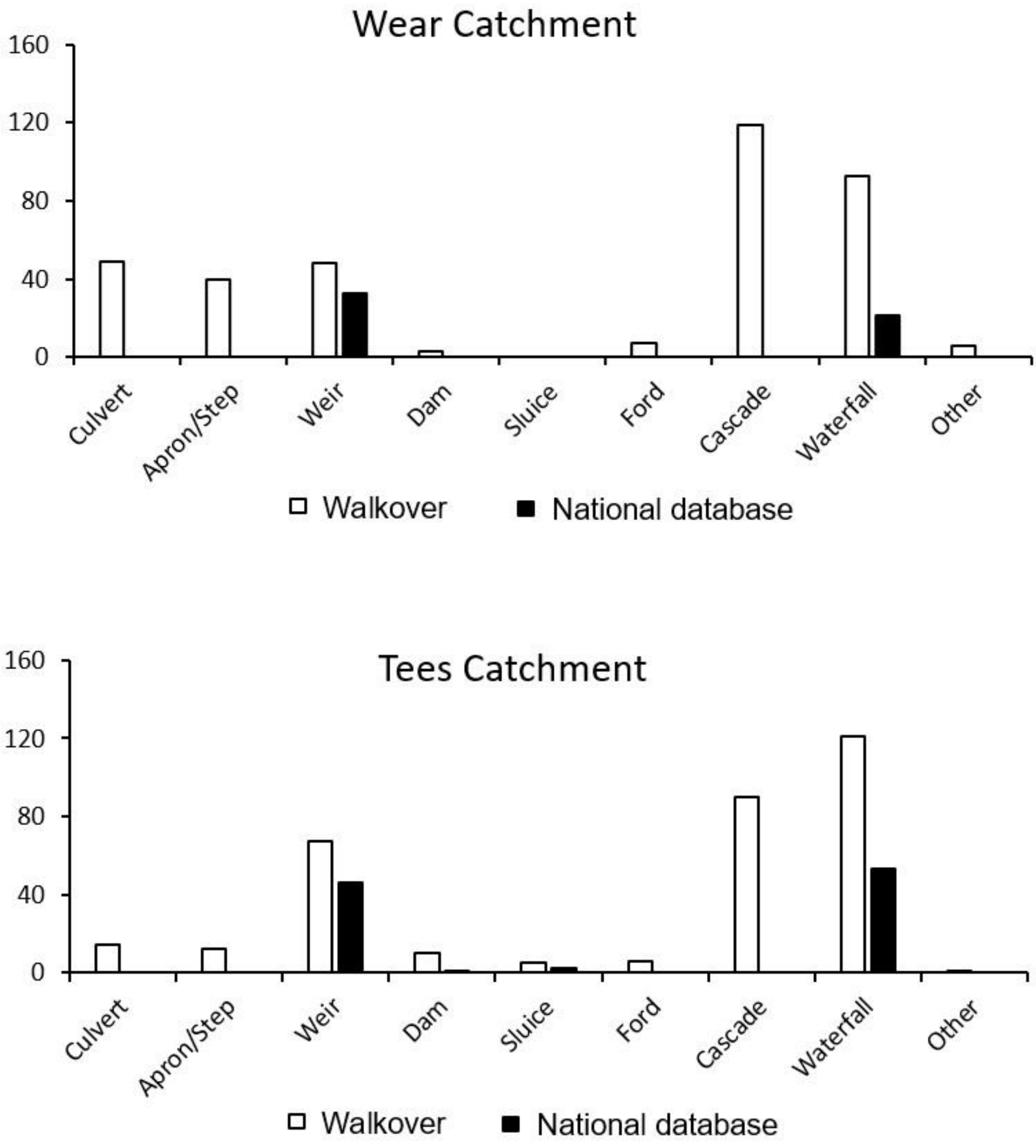

Figure 4. Different barrier types recorded in the walkover survey database and EA database on (a) the Wear and (b) the Tees catchment. Other refers to: collapsed bridge (n = 1), spillway (n = 4), concrete channel (n = 1) and tidal barrage (n = 1).

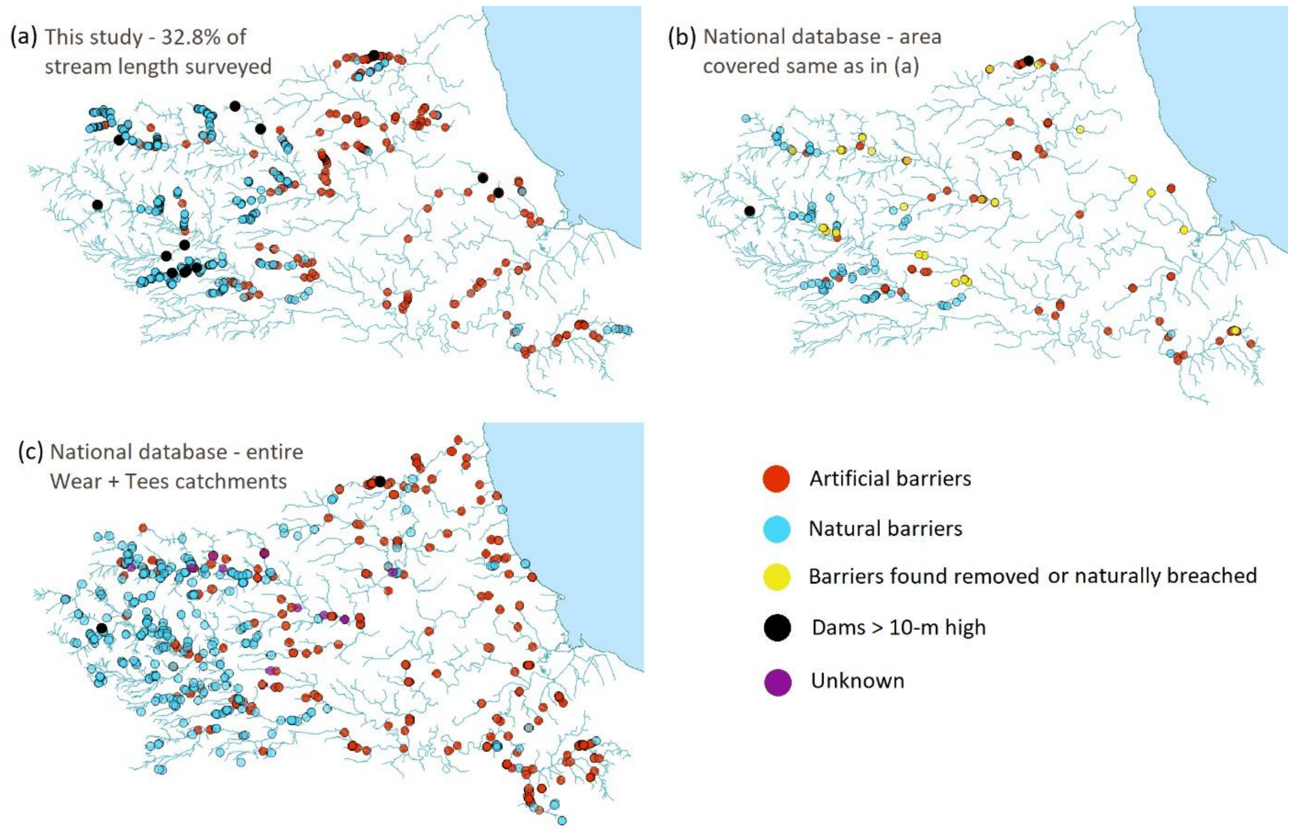

Figure 5. Locations of different types of barrier recorded in (a) walkover survey database, (b) National database under same walkover survey range and (c) National database for the entire Wear and Tees catchments. Purple circles: barriers classified as unknown in the national database.

Supplementary Information

Jingrui Sun, Shams M. Galib and Martyn C. Lucas

Are national barrier inventories fit for stream connectivity restoration needs? A test of two catchments

S1.1 Characteristics of the Wear and Tees catchments

The River Wear flows eastwards for about 110 km until reaching the North Sea at Sunderland. The catchment of the upper Wear is mostly characterised by upland heather and peat moors (Environment Agency, 2019a). The area is mostly rural and used to be the largest lead-zinc mining region in the world (Kelly, 2002). The landscape of the middle reaches of the Wear is mainly arable farmland, with numerous villages and some larger towns. The middle catchment has a long coal mining, sand / aggregate and shale extraction history close to the river (Neal *et al.*, 2000). The lower Wear catchment area is a mix of urban, industrial and arable land. The catchment area of the Wear is 1321 km^2 (Environment Agency, 2019a) and the total river network length is 752 km (OS Open Rivers 1: 25 000). The Wear is one of the most important Atlantic salmon *Salmo salar* and sea trout *S. trutta* rivers in England (Environment Agency, 2019b). The lower Wear suffered severe water pollution from the industrial revolution to the 1970s and salmon almost became extinct in the river. From the 1970s onwards pollution sources reduced through the decline of heavy industry and due to better water treatment, the salmon population began to recover, and in recent years the river has had the second highest annual salmon rod catch in England (Environment Agency, 2019b).

The River Tees' source is about 10 km south of the Wear's. The Tees flows eastwards for 160 km and joins the North Sea after passing Middlesbrough. The catchment area of the Tees is 1930 km^2 (Environment Agency, 2019a) and the total river network length is 1389 km (OS Open Rivers 1: 25 000). Most of the upper Tees catchment is characterised by upland heather and peat moors (Environment Agency, 2019a). Land cover of the middle reaches is mostly categorized as intensive agriculture land. The lower Tees and estuary is largely urbanized as well as having industrialized areas. The Tees was also a major salmon river until pollution and river barriers caused their decline in the late 19th and early 20th centuries. A tidal barrage, built 16 km upstream of the river mouth, opened in 1995, in order to limit the tidal movement of pollution and facilitate urban redevelopment. Although the Tees Barrage included a salmonid fish ladder in its design, and the water quality of the lower Tees and estuary has improved dramatically in the last 30 years, salmon and sea trout have remained at low abundance by comparison to the Rivers Wear and Tyne to the north (Environment Agency, 2019b).

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